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A MATHEMATICAL APPROACH TO DCS ARCHITECTURE FORMULATION.(U)
SEP 77 W P DOTSON
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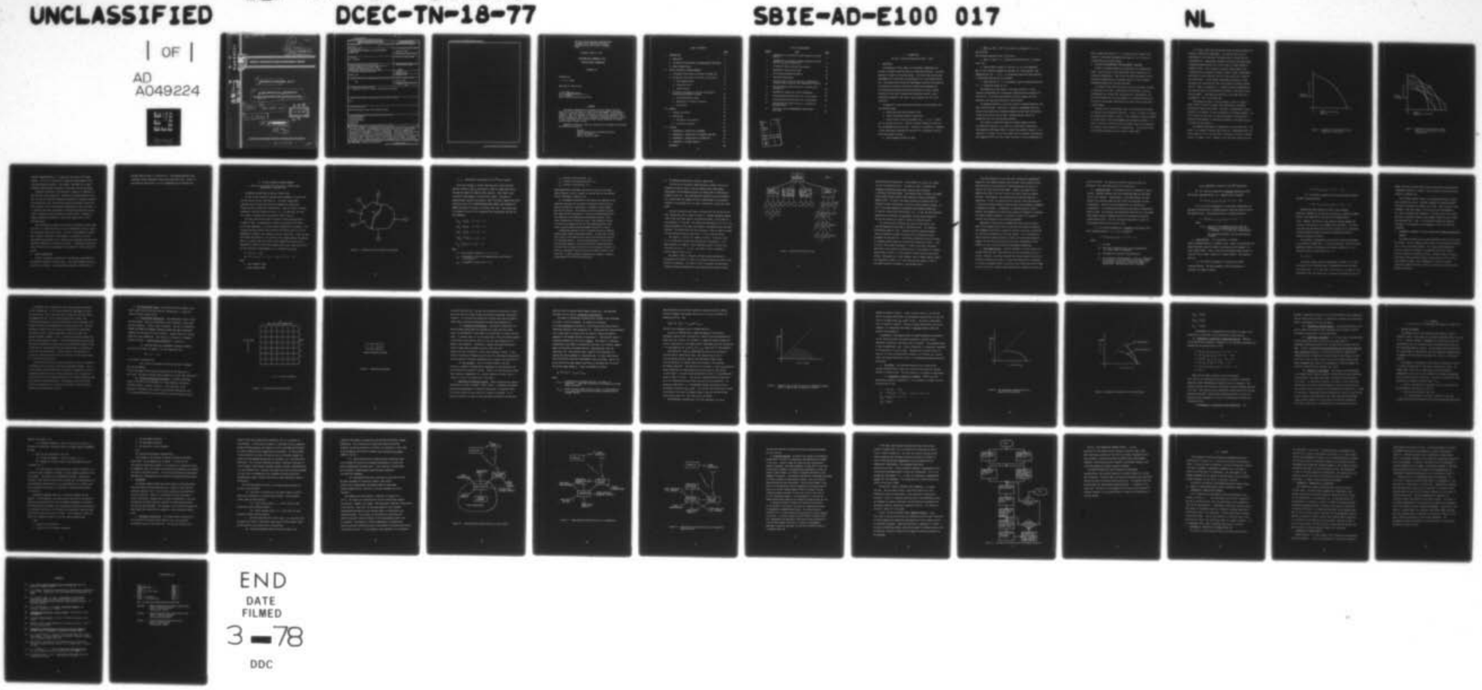

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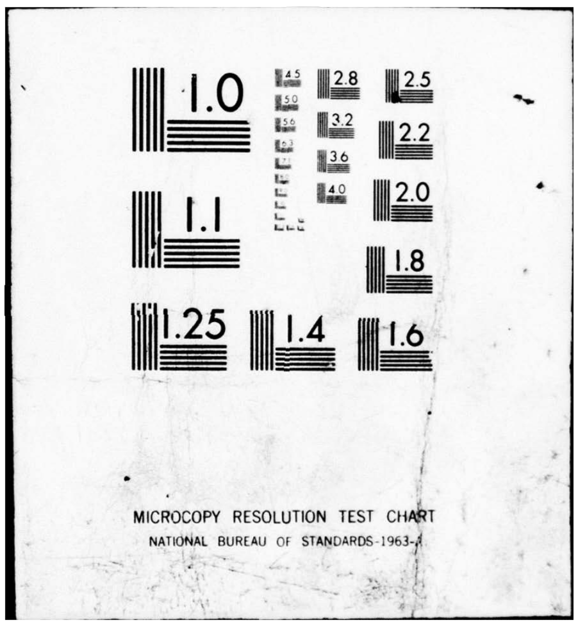
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This report develops a mathematical way of treating far-term DCS (e.g., DCS III) technical planning. The mathematical approach cannot solve all the problems, but it narrows the range of feasible alternatives. Thus, the methodology suggested is a management aid, not a replacement. With this approach, planning the DCS must be stated as an optimization problem. Therefore, high level planning issues and objectives must be translated into proximate and technically meaningful terms. When this is done, the solution can be sought. The report concludes with a proposed methodology and recommendations for implementation.

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A MATHEMATICAL APPROACH TO DCS ARCHITECTURAL FORMULATION

OCTOBER 1977

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FOREWORD

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I. INTRODUCTION

"Be alert, the world needs more Lerts." Anon

1. OBJECTIVES

The objective of this report is to develop a methodology for finding an optimal transition path for future DCS evolution. The total approach is based on a two-step process. The first step involves the development of the desirable architecture(s) for a far-distant future DCS. The second step involves the development, analysis and evaluation of alternative transition plans which bridge the gap between the existing baseline system and the perceived goals of future systems. Selection of the "best" alternative(s) therefore implies a joint optimization problem of the "best" future together with the "best" transition.

An approach for solving the above problem can be developed along the following steps:

a. Define the best Future System(s) (FS).

b. Define the present Baseline System (BS).

c. Select several Transition Systems $\{TS_i : i = 1,2,\cdots\}$ which cost C_i and give service S_i. Define "Distance" between TS_i and FS as $\overline{TF}_i$ and between BS and TS_i ad $\overline{BT}_i$. "Distance" is defined as a "measure" in some sense which indicates the shortfall of a suboptimal solution versus the optimal solution.

d. Define Budget Availability (BA).

e. $\max_{TSi} f(S_i, \overline{BT}_i^{-1}, \overline{TF}_i^{-1})$ such that $C_i \leq BA$ where $f(\cdot,\cdot\cdot,\cdot)$ is some function.

The following questions occur to the alert:

a. What is "best"; i.e., how does one decide that FS_i is "better than" FS_j?

b. Exactly what is meant by "service" S_i; can it be measured? What is the "Distance" between two systems; can it be measured? How should the set $\{TS_i : i = 1,2,\cdots\}$ be selected; could the "best possible" TS be omitted from the set by oversight?

c. What function $f(\cdot,\cdot,\cdot)$ is proposed; could a different choice for $f(\cdot,\cdot,\cdot)$ change the choice of TS_i?

The objective of this report is to answer question a. and to indicate a methodology for architectural formulation and evaluation of the best FS. In so doing we find hints on how to answer the other questions, but these are deferred for later efforts.

In answering question a, we do not provide a proposed design for the DCS in detailed terms. What we do is develop a methodology which can discover and quantify the tradeoffs between the high level architectural issues of the DCS for the far-term. Detailed design studies are appropriate only for near-term DCS planning.

This report is therefore primarily oriented towards far-term architectural studies of, e.g., DCS III, a term used to denote the next generation DCS beyond 1985. To present the approach, however, it is necessary to "freeze" time at the present and then consider the question: What should the DCS look like X years from now? In the consideration of

how to answer that question, "X" is taken to be far enough in the future to avoid being overwhelmed with details; i.e., we are not constrained by the present design.

2. THE NEED FOR MEASUREMENTS AND MEASUREMENT TECHNIQUES

The DCS is intended primarily to meet DOD crisis communication needs. The servicing of other needs under benign conditions is a secondary consideration. Thus the DCS should be designed to assure survivable communications of adequate capacity to force elements deployed worldwide under wartime conditions.

In efforts to meet this design goal various attributes are posed as desirable for the DCS. Among these are flexibility, security, interoperability, reliability, maintainability, restorability, etc. Cost effectiveness must also be admitted as a design goal because of the need to get maximum communications for every dollar spent under a limited budget.

Because of the limited budget, none of the desirable attributes for the DCS can be regarded as absolute. In fact, all goals are subject to tradeoff under economic analysis. This seemingly innocuous statement is at the source of the DCS management and engineering problems. In order to trade off different design attributes, each must be measured in some way, either objectively or subjectively. The relative worths of different attributes must be similarly established.

It is quite likely that the relative worths of DCS attributes will always be subjectively established. The same may hold for the measurement of some individual attributes such as flexibility and interoperability. Nonetheless, whenever possible an attribute should be measured quantitatively and in such a way as to make subjective tradeoffs easier. As an analogy to the guns versus butter curve frequently seen in economics textbooks, Figure 1 shows a hypothetical survivability versus capacity curve at fixed dollars for a specific DCS architecture. If the system is designed to maximize a single attribute, say survivability, then a zero capacity (useless) system results. What is "reasonable" is a subjective decision depending on the relative worths of the different attributes in the minds of the decision makers. Some objective decisions can be made from such a presentation. This is discussed next.

The analogy of Figure 1 can be extended as shown in Figure 2. Here a family of curves is shown, each representing a different architectural option for the DCS. From such a presentation it may be possible, in principle, (if one architecture is uniformly dominant, i.e., if all points on that curve lie above any other) to conclude that a particular architecture is preferable regardless of the desired mix of survivability and capacity.

The examples given above are hypothetical and oversimplified. This report is an attempt to develop the outlines of a methodology which will relate some (not all) of the desirable attributes of the DCS in formats similar to Figures 1 and 2. Whether or not the reader agrees with the

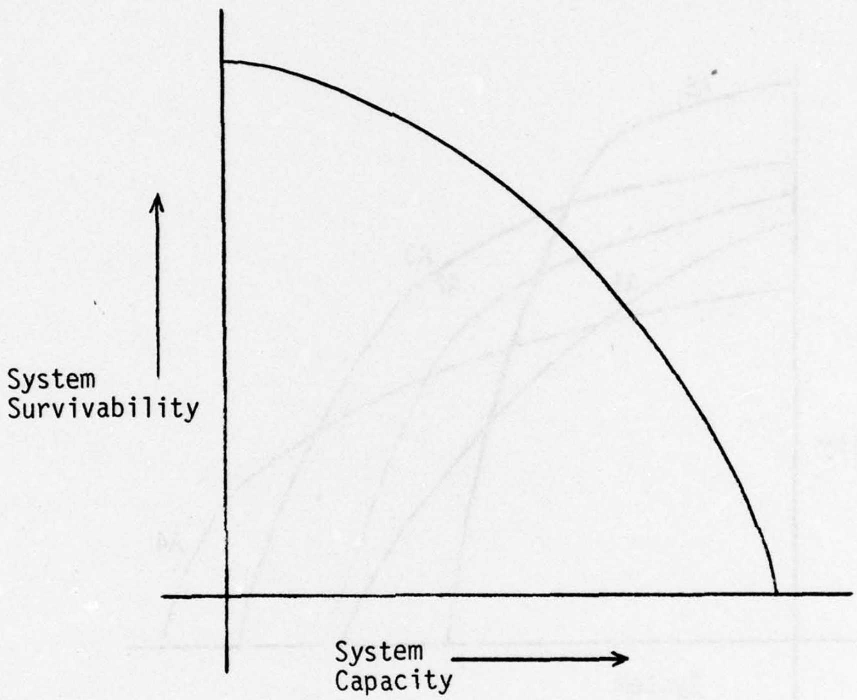


Figure 1. Hypothetical survivability versus capacity at fixed dollars

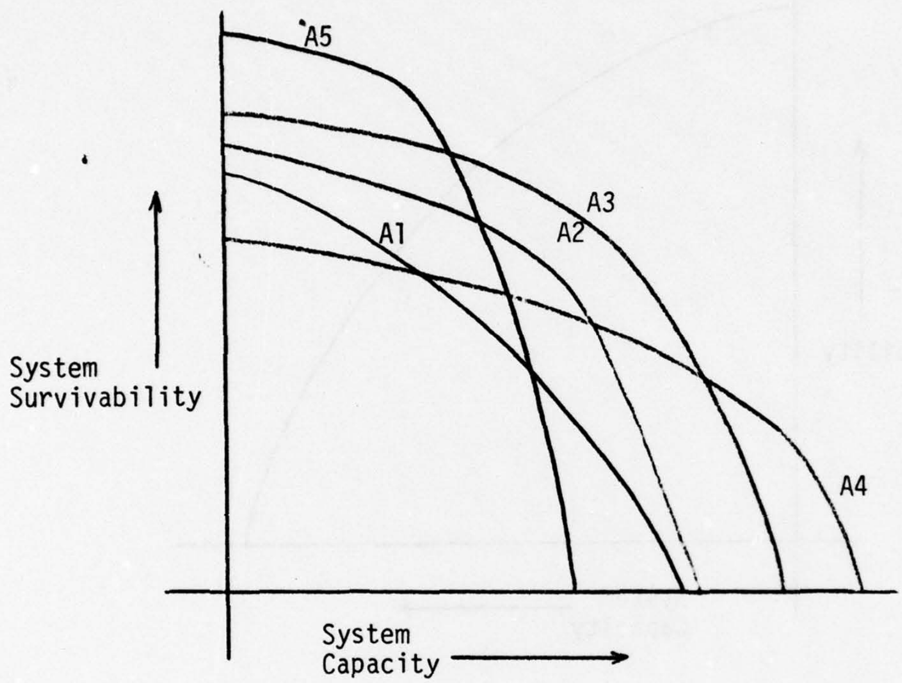


Figure 2. Hypothetical survivability versus capacity at fixed dollars; various architectures

approach suggested herein it is hoped that two things will become evident. The first is the need for quantitative measurement of DCS attributes wherever possible. The second is the need for a formal mechanism relating these attributes to each other and the DCS budget.

Technical planning for the future DCS is equally as important as efficient day to day operations. Without well defined technical plans and a visible and therefore improvable framework for technical planning, system evolution, cost, and services cannot be efficiently controlled. Since planning involves uncertainties proportional to the lead time, it is important that plans be updated as information becomes more precise. Ideally, technical planning should be a routine affair, repeated to produce updated plans whenever a significant change occurs in the planning factors.

Past architectural studies of the DCS have indicated in broad scope the merit of a future DCS which will be a predominantly digital, secure, and integrated common user system. The cost of new hardware to support such a system, the design of the hardware, and whether or not user requirements would support such a system at any projected time need to be adequately addressed in architectural studies. Techniques to ameliorate these difficulties can be developed if the problem is sufficiently well stated.

3. REPORT ORGANIZATION

Section II develops a description of the DCS and a description of the technical problem in abstract terms. Only those features we see as essential are included. Having defined the problem in Section II, we

consider ways to solve it in Section III. The proposed approach uses techniques either developed or being developed within DCEC. Section IV concludes the report with a list of recommendations for further work.

II. THE DCS TECHNICAL PLANNING PROBLEM

"... make sure that people think they have a problem before volunteering a solution."[1]

1. AN ABSTRACT DESCRIPTION OF THE DCS, OUTSIDE VIEW

The DCS can be externally characterized by demands for service and threats against service (see Figure 3). The small square boxes represent user installations which place demands for connections through the DCS to other user installations. The cut (crack) in the DCS represents a possible threat to service, i.e., an inability, for whatever reason, to connect users on opposite sides of the cut.

The user installations shown in Figure 3 can be characterized in a number of ways: by geographical location, by national affiliation, by military department, or by other special communities of interest. The relevant characterizations from an overall DCS design point of view are geographical location, user community, and user need lines. Recalling that the primary DCS objective is to provide crisis communications, the problem then is to predict that collection of user communities and that set of geographical locations within each community which will need such service. Let the collection be designated as $\mathcal{U}$, a collection of sets U_k:

$$\mathcal{U} = \{U_1, U_2, \cdots, U_K\}$$

$$U_k = \{(i, x_i, y_i) : i = 1, 2, \cdots, I_k\};\ k = 1, 2, \cdots, K$$

where

k : user community index

i : user location index

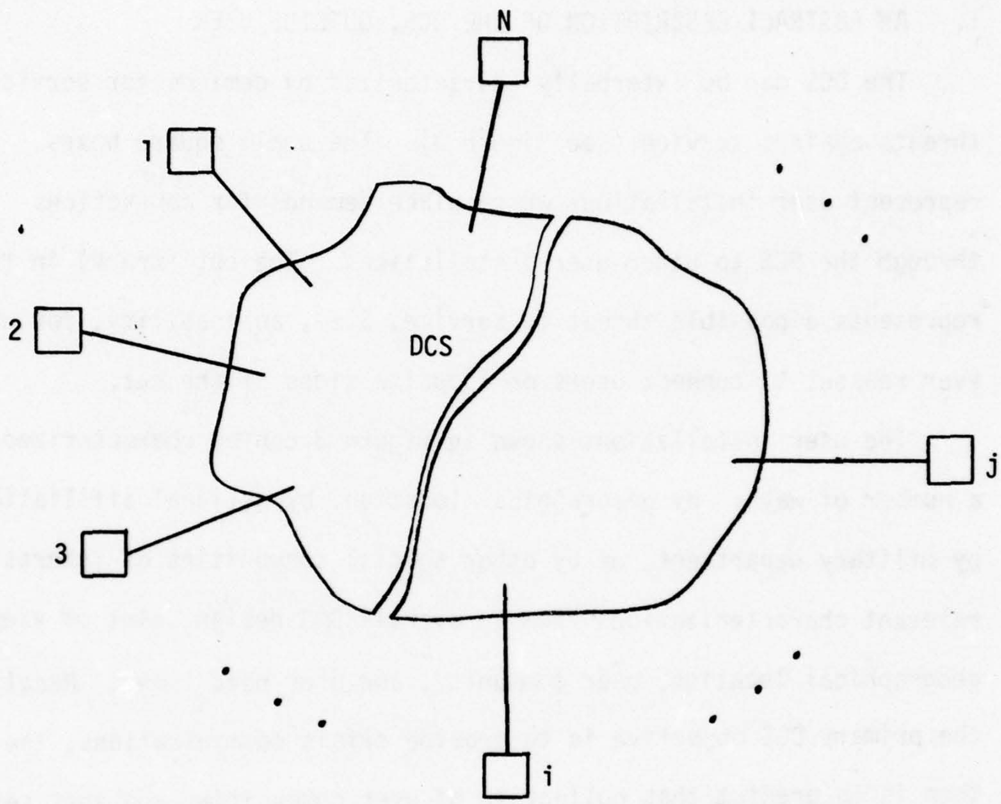


Figure 3. An abstract view of the DCS from outside

x_i, y_i : geographical coordinates of the $i^{\underline{th}}$ user location

Each user location is further characterized by that (possibly improper) subset of $\bigcup_{k=1}^{K} U_k$ with which it needs to communicate and by the type and amount of communications required. This allows interoperability requirements to be explicitly stated. The types of communications required are typically clear voice (CV), secure voice (SV), interactive data (ID), narrative/record data (NRD), and facsimile (F). Amounts are given in Erlangs or bits/busy hour (BH). The problem then is to predict a set of crisis communications requirements matrices for each community.

$R_{cv_k} = [\alpha_{ij}]_k$; $k = 1,2, \cdots, K$

$R_{sv_k} = [\beta_{ij}]_k$; $k = 1,2, \cdots, K$

$R_{id_k} = [\gamma_{ij}]_k$; $k = 1,2, \cdots, K$

$R_{nrd_k} = [\sigma_{ij}]_k$; $k = 1,2, \cdots, K$

$R_{f_k} = [\rho_{ij}]_k$; $k = 1,2, \cdots, K$

where

i,j : user location indices; $i,j = 1,2 \cdots, N$

α_{ij} : Erlangs/BH of clear voice communications from location i to location j

β_{ij} : Erlangs/BH of secure voice i to j

γ_{ij} : Bits/BH of interactive data i to j

σ_{ij} : Bits/BH of narrative/record data i to j

ρ_{ij} : Bits/BH of facsimile data i to j

These communications requirements matrices will turn out to be slowly varying functions of time in response to changing levels of international tension, technological capability, etc.

It is reasonable to assume that in the event of war some part of the adversary's resources will be devoted to disrupting the DCS as well as against individual user installations. The design of the DCS should take this into account. Thus additional prediction problems are raised. What subset of user installations is likely to be attacked and how will this change the crisis communications requirements matrices? (This allows consideration of flexibility issues.) What elements of the DCS are likely to be attacked and how will this change the ability of the system to handle communications requirements (survivability issues)?

A conservative approach to the first question would be to construct composite upper bounding requirements matrices. For each type of service the i,j entry in the composite matrix would be the maximum over some set of conceivable scenarios. As for the second question, it can be shown that the answer depends on the value of particular communicating pairs, the reliability of elements within the DCS, the structure of the DCS, the adversary's knowledge of these factors, and the resources devoted to the attack [2]. A useful technique in addressing this problem is to adopt a gaming approach in the initial DCS design work.

2. AN ABSTRACT DESCRIPTION OF THE DCS, INSIDE VIEW

The DCS can be internally characterized by hardware devices and groupings of devices used to satisfy communications requirements. Associated with the hardware devices are trends both in technological capability and cost. Cost considerations naturally involve allocation of a constrained total budget as well as amortization of the present inventory of equipments,and, once again, predictions of what the future holds.

One way of depicting the range of alternatives for the DCS in the near, mid and far term is shown in Figure 4. Another apparently popular view is that the figure depicts the planning problem, in the form of a tree structure, for the DCS. No attempt has been made to fill in all the possible branches of the tree; only enough is presented to show the major features. The problem with the tree structure is that it tends to seduce one into forming erroneous conclusions. This is discussed below.

The figure is laid out in a number of levels. At the top (level 0) is a single node labeled "DCS architectural alternatives." This node branches to a number of nodes immediately below in what will be referred to as level 1. In turn, each node on level 1 branches to several nodes on level 2, etc..

The nodes of level 1 represent different system partitioning alternatives for the DCS in terms of the degree to which the users of the system are integrated. The nodes of level 2 represent the generically different switching methods which could conceivably be used to realize

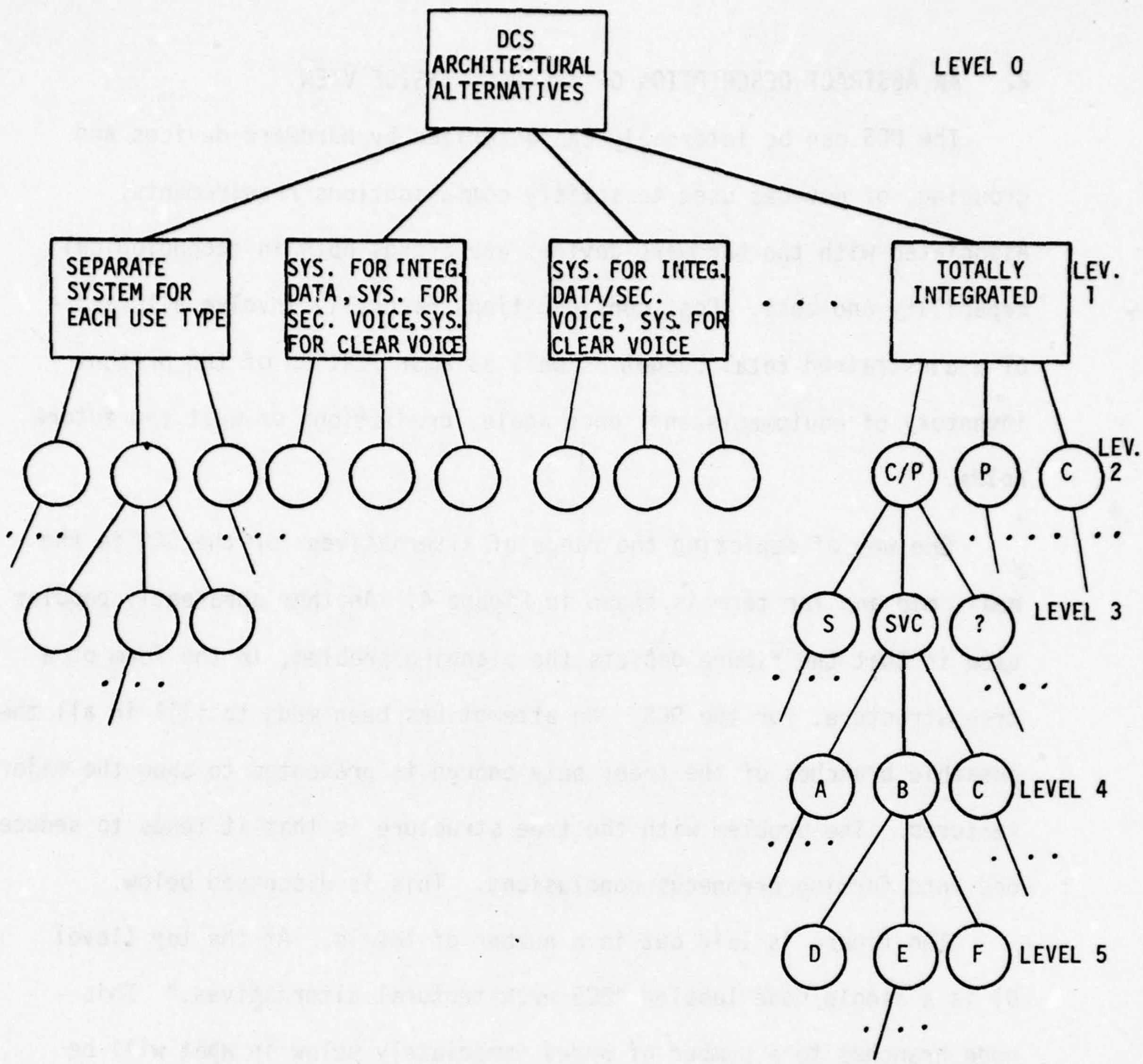


Figure 4. Hypothetical DCS decision tree

the partitioning alternatives. These methods are circuit (C), packet (P) and circuit/packet (C/P). The nodes of level 3 represent the different switching concepts which could be used to realize a particular switching method. The examples shown in Figure 4 are SENET [3] and SENET Virtual Circuit (SVC) which fall under the switching method of C/P. On level 4 the nodes represent the possibilities for different switch architectures to realize a given switching concept. At level 5 the nodes represent the hardware and software alternatives to realize a given switch architecture, etc. In sum, the tree structure represents one technique for aggregation of descriptive features of the DCS and displays the range of choices in planning the DCS.

The tree structure indicates, but does not show clearly, the coupling between decisions made at different levels. For example, a partitioning study at level 1 cannot be properly conducted without costing information related to transmission, switching, and access equipment for the total DCS. The costing information can only be found by a network design study for the total DCS conducted at level 2. Even at level 2 the costing information is likely to be quite inaccurate, particularly with regard to switching costs, in the absence of a network design study at level 3 for the purpose of inferring switch functional design, loading, and cost. Note, however, that if network design studies are conducted at levels 2 or 3, then partitioning studies at level 1 have been explicitly performed in considerable detail.

From the foregoing it can be seen that architectural development/ design is a very complex problem involving many closely coupled factors. Good decisions are not possible by looking ahead only one level at a time (as the tree structure may tempt). Ideally, one would like to examine every node in the last level of the tree to make the optimum decision. Unfortunately, the proliferation of branches makes this impractical; in fact, the possibility of arriving at the same end point in the tree by taking different paths may make such an approach inadequate on theoretical grounds. Consequently, an approach based on network analysis and aggregation of descriptive features of hardware is suggested. The network analysis approach is discussed in section III; hardware features are discussed in the following paragraphs.

Regardless of the particular methodology used to design the DCS, data on the hardware devices used to construct the system are required. The fundamental difficulty in technical planning of the DCS is balancing the cost and the capability of the total system. This, coupled with a view of the DCS as being basically a (family of) connecting network(s), suggests the following classifications and data requirements for DCS hardware as used in the architectural development methodology.

a. <u>Base Communications</u>. Terminal equipment and local switches are located within the user installation and are not considered as part of the DCS. However, since they represent the ultimate sources and sinks of information handled by the DCS, a minimal characterization is necessary. All terminal equipments within a particular user installation may be homed on one or more local switches which represent the information sources and

sinks for the DCS. The necessary information regarding these was developed in the requirements matrices of subsection 1.

b. Terrestrial Grid. The terrestrial grid is composed of concentrators, backbone switches, and links connecting these to each other and to local switches. Concentrators, as the name implies, may have several local switches homed on them as well as being homed on other concentrators. (We also allow the possibility of switching by a concentrator.) In turn, backbone switches may have several concentrators homed on them. The structure and hierarchical definition of a survivable and economic system of adequate capacity can be deduced by applying network design tools. This will be further discussed in section III. The necessary data to drive the tools are:

(1) An initially assumed set of potential concentrators with their characterizations, i.e., a set of sextuples:

$$C = \{(\ell, f_\ell, c_\ell, d_\ell, x_\ell, y_\ell) : \ell = 1,2, \cdots, L\}$$

where

ℓ : an index

f_ℓ : functional characterization of the concentrators; i.e., voice, data or integrated

c_ℓ : throughput (or capacity) characterization

d_ℓ : cost (dollars) characterization. This is a prediction, in the form of a Cost Estimating Relationship (CER), which depends on capacity, function and number of terminations. O&M costs may also be included.

x_ℓ, y_ℓ : geographical location of the ℓ^{th} concentrator.

(2) An initially assumed set of potential backbone switches with similar characterization, i.e., another set of sextuples:

$$B = \{(m, f_m, c_m, d_m, x_m, y_m) : m = 1,2, \cdots, M\}.$$

(3) An initially assumed set of links which interconnect the previously discussed sets of hardware devices with each other as well as the satellite grid. The characterization is slightly different:

$$L = \{([i,j], f_{i,j}, c_{i,j}, d_{i,j})\ i,j = 1,2, \cdots\}$$

where

[i,j] : indices for the hardware devices at the two endpoints of a bidirectional link from i to j. [·,·] becomes (·,·) if the link is undirectional.

The remaining parameters have the same meaning as before.

c. Satellite Grid. It is unrealistic to consider satellite communications as a separate issue. Rather, the satellites and ground terminals should be treated as two more sets of hardware in a total system context. Such a view allows the network design process to treat the "mix of media" problem as a systems problem. The necessary data are:

(1) An initially assumed set of satellites and their characterizations. The same parameters, with the exception of location, are needed as before.

$$S = \{(n, f_n, c_n, d_n) : n = 1,2, \cdots,N\}.$$

(2) An initially assumed set of satellite ground terminals and their characterization.

$$G = \{(t, f_t, c_t, d_t, x_t, y_t) : t = 1,2, \cdots,T\}.$$

Economics has been referred to often in the preceding discussion. Demands for service are satisfied by a system of hardware devices. The system cost is the sum of all hardware device costs. However, the ability of the system to satisfy demands for service is not the sum of all hardware device abilities. This fact, along with the observation that the total system cost is constrained by the DCS budget, creates an economic optimization problem in technical planning of the DCS.

The problem is compounded by the fact that the exact DCS budget is not known for future years. It must be predicted. Thus we have the additional problem of formulating an economic constraint, D, as a function of time, national mood, etc.; i.e.,

$$D = f(T,\cdot).$$

Even given D, other economic problems must be solved. One is the allocation of D to different types of communications services and/or user communities. It is clear that if more money is allocated to, say, subsystem A, then less money can be allocated to subsystem B; thus the

budget allocation problem couples the DCS problem even when physically independent networks are assumed. See for example the multidivisional problem in reference [4].

Still another economic factor is the amortization rate of equipment currently in service. The best technique of assigning economic lifetimes to hardware and systems is not clear. What is clear is that equipment in the field today, or to be put in the field tomorrow, represents an enormous DCS investment. The sheer size of this investment has a significant impact on the economic feasibility of an otherwise excellent plan. Thus, if a given plan requires the premature retirement of large amounts of DCS hardware, it will not likely be acceptable.

3. AN ABSTRACT STATEMENT OF THE DCS ARCHITECTURE FORMULATION/EVALUATION PROBLEM

The preceding subsections have been developing pieces of the overall DCS problem. In this subsection these pieces are collected and organized into a single time phased problem. This single problem depends on solving a sequence of problems in estimation theory which involve prediction theory and probability theory. Network analysis, involving graph theory and optimization theory, is then applied to the results of the estimation problem. Next, management is involved in making subjective tradeoff decisions on the mix of attributes possible within economic constraints.

As alluded in the introduction, time phasing enters the problem in the following way. In far term architectural development we would like to discover, with as much precision as possible, what the future DCS should look like. By far term we simply mean a future time sufficiently advanced so that the architecture is not influenced by the present inventory of DCS hardware and its amortization rate. Once the necessary outlines of the far-term DCS architecture are established, one needs to solve a second problem which takes into account the present equipment inventory. This is the mid-term planning problem and can be stated roughly as follows. Given the present DCS design and some desirable far-term DCS architecture(s), what mid-term DCS design is best suited both for transitioning from the present design, and towards one of the far-term architectures. Finally, there is the near-term, or day-to-day, problem of maintaining the efficiency of the present design as it evolves into the future.

The mid-term and near-term planning problems are seen as successive refinements of the far-term architectural development problem. That is, as the planning lead time decreases, predictions on demands for service, technology capacility and cost, design constraints, etc., become more accurate and allow a more detailed definition of the DCS through the same basic technical planning mechanism. Consequently, only the far-term problem is developed since it contains the essential features without becoming overly burdersome in details.

a. DCS Architectural Issues. DCS planning involves several "high level issues" which drive more detailed considerations. A short discussion of these issues follows.

(1) Partitioning Alternatives. One architectural issue is that of partitioning. This can be displayed in two dimensions: service type and user community. Figure 5 shows an example. The DCS is a connecting network (or family of networks) designed to meet the need of each user community for each type of service required. Suppose there are I service types and K user communities. Then there are a maximum of $I \cdot K$ demands placed on the DCS. A partitioning alternative is a choice of:

(a) How many physically independent connecting networks will be built to meet all demands. Call this number NN; then

$$NN = 1, 2, \cdots, I \cdot K$$

is the range of possibilities.

(b) A set of assignment rules which maps the $I \cdot K$ demands onto the NN networks.

Clearly the number of partitioning alternatives for the future DCS is very large. How does one decide which alternative is best? (See subsection b.)

(2) Switching Technology Alternatives. Switching technology issues of the DCS can be displayed in a single dimension, the generic switching concept, as shown in Figure 6. The choice here is not necessarily dictated by prior choice of partitioning alternatives since it is conceivable that data can be handled by circuit switching or voice

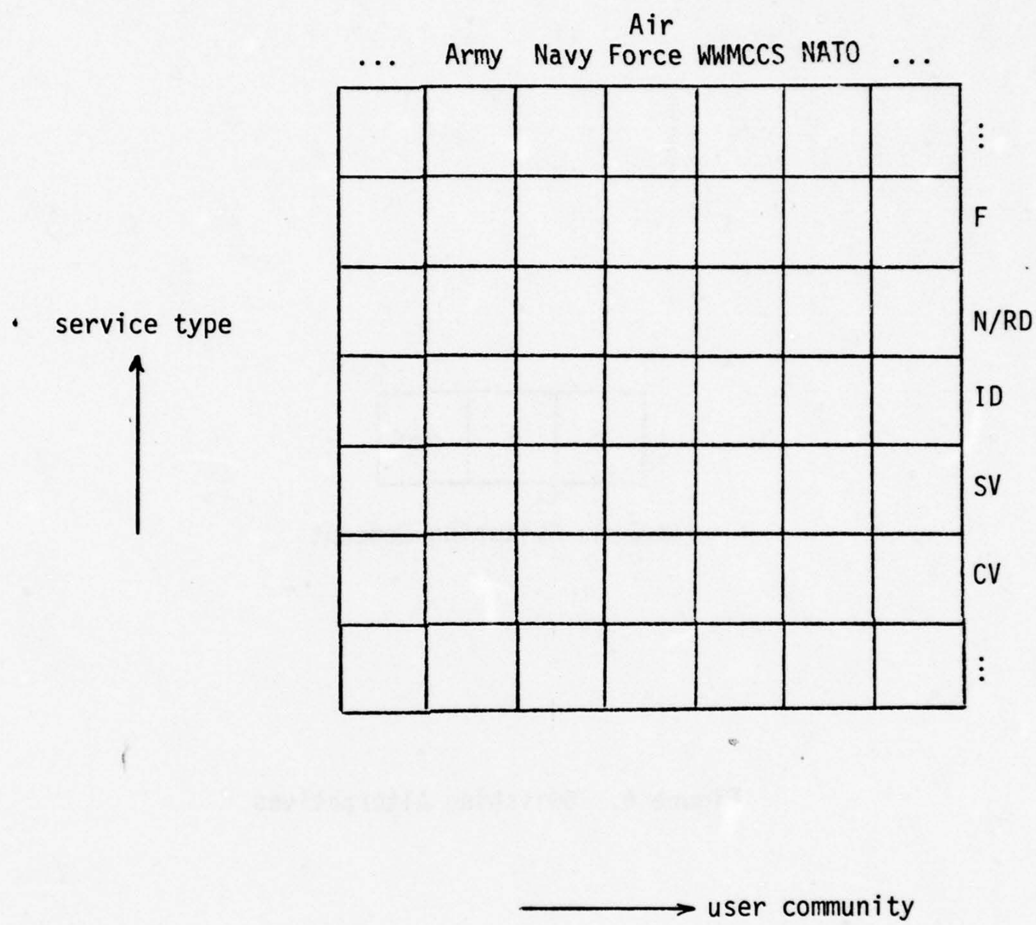
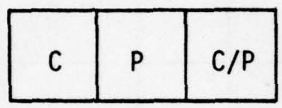


Figure 5. Partitioning Alternatives Matrix



Generic Switching Concept

Figure 6. Switching Alternatives

by packet switching [5]. How does one decide which alternative is best? How do the choices of partitioning and switching technology alternatives interact? If a partitioning alternative involves more than one network, should several switching technologies be used? (See subsection b.)

(3) Hierarchical Alternatives. Hierarchical alternatives for the DCS cannot conveniently be displayed on a page since this issue covers an astronomically large number of possible ways to connect the DCS users. In general terms, it can be argued that a fully distributed network is best from a survivability point of view, but such networks are, in general, not economical. Conversely, a network with many hierarchical levels is best from an economics point of view, but such networks are less survivable. Exactly what structure is best? Is the choice of structure influenced by prior choice of partitioning alternative? Does the choice of switching technology have an impact? (See subsection b.)

(4) Mix of Media. The mix of media problem of the DCS involves a tradeoff of communications dependence on the terrestrial and on the satellite resources of the DCS. There is no realistic way to treat these resources independently in a system context, and so this issue is properly a part of the hierarchical issue above.

b. Objectives of Technical Planning. Several questions were posed in subsection 3,a, above, related to "best" choices. A technique for making quantitative measurements of differing alternatives is necessary before it can realistically be said that one is superior to another. It is therefore necessary to agree on some measurable attribute of the DCS and

decision rules for making choices among alternatives. The measurable attribute will be called a performance characteristic.

Any number of performance characteristics related to the attributes in section I could be proposed. We propose the following.

Let a DCS alternative be defined by a partitioning choice and switching technology choice(s) (from subsection 3,a). Within each DCS alternative there are a great number of possibilities for specific connecting networks composed of the hardware devices of subsection 2. Each possible family of connecting networks will be called a design. Each design is a detailed accounting of such things as hierarchical structure, mix of media, numbers, types and locations of hardware devices, interconnecting links and capacities, etc. Each design within a specific DCS alternative can satisfy the service demands in a measurable way. In fact, there are at least two distinct and useful measurements that can be made. One will be called the utility under benign conditions U_b; the second will be called the utility under attack U_a. These are defined as follows:

$$U_b = \sum_k \sum_{i,j} (1 - P_{i,j,k})\, \alpha_{i,j,k}$$

where

$\alpha_{i,j,k}$: predicted service demand from user i to user j in community k. (Note that conversions from Erlangs to bits/BH have to be made.)

$P_{i,j,k}$: Grade of service (GOS) for voice traffic or the fraction of $\alpha_{i,j,k}$ that must be discarded to obtain acceptable delays for data traffic.

Now imagine that an intelligent adversary attacks the design, removes exactly W elements and chooses that set of W in a way to minimize the remaining utility. Then

$$U_a(W) = \sum_{\kappa} \sum_{i,j} (1 - P_{i,j,k}(W))\, \alpha_{i,j,k}.$$

This will be a drawdown curve if plotted against W.

U_b and U_a as defined form a composite measure of the design's throughput capacity, GOS, survivability, flexibility, and interoperability. These last two "ilities" are included in a subjective manner through the initial construction of the communications requirements matrices (subsection 1; in the equations for U_b and U_a let $\alpha_{i,j,k}$ range over all requirements).

Each design will have an associated cost which can be determined from the data of subsection 2 above. Now imagine the set of all possible designs within a specific DCS alternative; then exclude from consideration all designs whose cost exceeds D, the predicted DCS budget constraint. The remaining set of designs is almost astronomically large; nonetheless we imagine measuring U_b and $U_a(W)$ for each design at some fixed W. For each design, then, we have a point in a two-dimensional space as shown in Figure 7. Thus, we have a mechanism which displays the set of all admissible designs within one specific DCS alternative. The mechanism establishes a 1-1 correspondence between each design and its performance, the points $(U_b, U_a(W))$. As an aside, the reason that no points are plotted in the upper pie shaped region is that, by the definitions, $U_a(W)$ must be equal to or less than U_b for any design.

The performance characteristic of a DCS alternative can now be

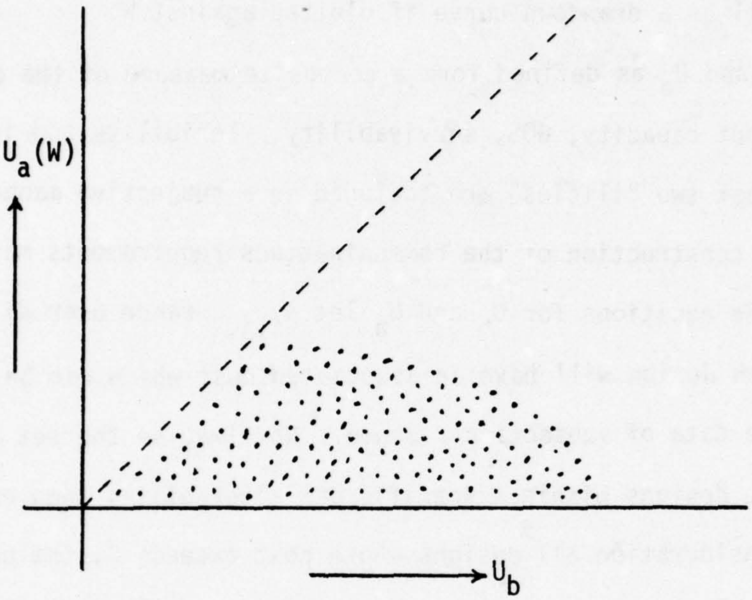


Figure 7. The pairs (U_b, $U_a(W)$) for the set of admissible designs within a specific DCS alternative at fixed W

defined in terms of Figure 7. Since a rational choice is to pick the points of maximum performance, the performance characteristic is just the locus of extreme points (U_b, $U_a(W)$) in the E - NE sector of the figure. This is plotted in Figure 8. The set of points forming this line can be thought of as representing the subset of <u>dominant</u> designs within the specific DCS alternative.

A mechanism is now apparent both for choosing among DCS alternatives and for selecting within the chosen alternative a specific design (desirable hierarchical structures and mix of media). As an example, Figure 9 shows a hypothetical case. Clearly alternative 1 is preferable regardless of the desired mix of U_b and $U_a(W)$. Choosing this mix then points to a specific (in terms of hierarchical structure, mix of media, etc.) design within the chosen alternative by the 1-1 correspondence between design and performance.

c. <u>The Problem</u>. The foregoing discussion has introduced the concepts and definitions necessary to define the DCS technical planning problem in concrete terms. The total problem is a sequence of subproblems.

(1) <u>Subproblem a, Prediction of Demands</u>. Referring to the definitions contained in subsection 1, it is necessary to predict for the desired point in time:

$$\mathcal{U} = \{U_1, U_2, \cdots, U_K\}$$

$$U_k = \{(i, x_i, y_i) : i = 1,2, \cdots, I\}_K \; ; \; k = 1,2,\cdots,K$$

$$R_{cv_k} = [\alpha_{ij}]_k \; ; \; k = 1,2,\cdots,K$$

$$R_{sv_k} = [\beta_{ij}]_k$$

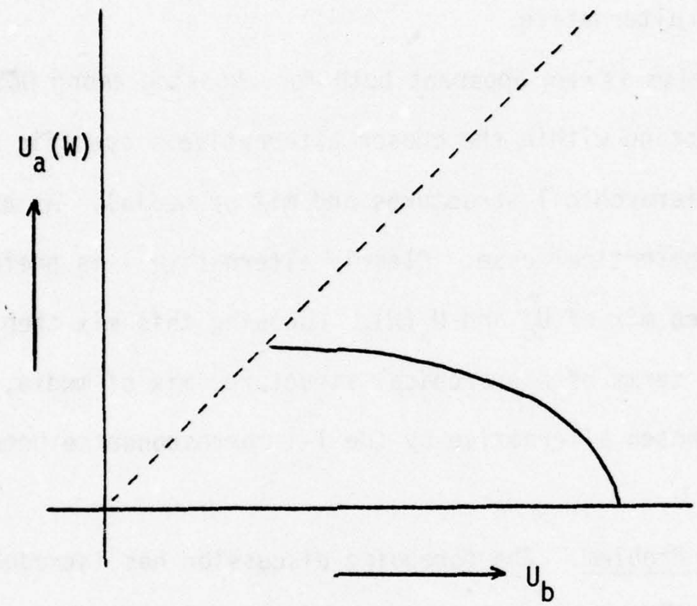


Figure 8. The performance characteristic of a specific DCS alternative

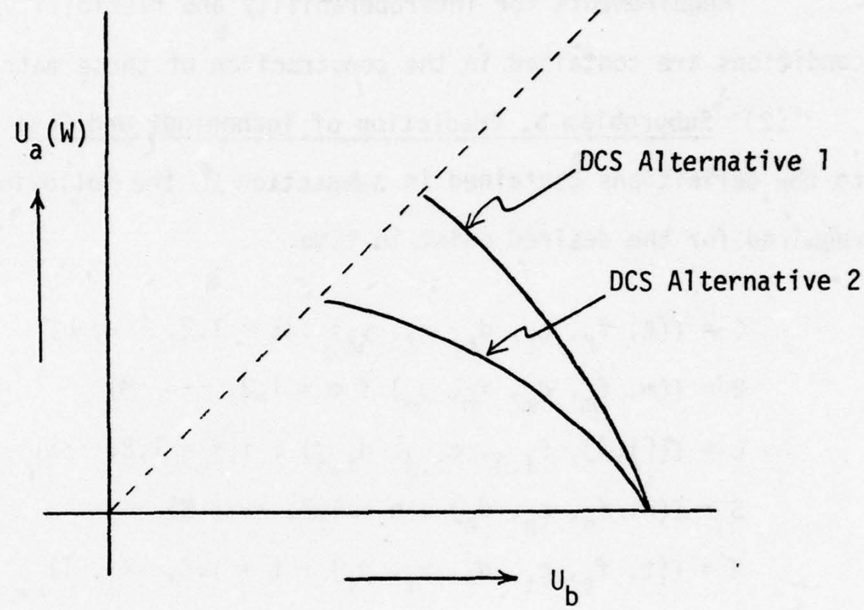


Figure 9. Hypothetical comparison of DCS alternatives

$$R_{id_k} = [\gamma_{ij}]_k$$

$$R_{nrd_k} = [\sigma_{ij}]_k$$

$$R_{f_k} = [\rho_{ij}]_k.$$

Requirements for interoperability and flexibility under crisis conditions are contained in the construction of these matrices.

(2) Subproblem b, Prediction of Technology and Cost. Referring to the definitions contained in subsection 2, the following predictions are required for the desired point in time:

$$C = \{(\ell, f_\ell, c_\ell, d_\ell, x_\ell, y_\ell) : \ell = 1,2, \cdots, L\}$$

$$B = \{(m, f_m, d_m, x_m, y_m) : m = 1,2, \cdots, M\}$$

$$L = \{([i,j], f_{i,j}, c_{i,j}, d_{i,j}) : i,j = 1,2, \cdots\}$$

$$S = \{(n, f_n, c_n, d_n) : n = 1,2, \cdots, N\}$$

$$G = \{(t, f_t, c_t, d_t, x_t, y_t) : t = 1,2, \cdots, T\}$$

$$D = f(\tau, \cdot).$$

There will be several versions of each of the above sets; one for each conceivable (and feasible) variation of functional capability and/or implementation scheme for the set in question. One possible variation would consider the problem of making lease/buy decisions in the DCS. Such decisions can be handled by assuming each of the various possible alternatives, appropriately modifying the CER's in each, and determining the consequences in terms of the performance characteristic introduced earlier.

(3) Subproblem c, Formulation of DCS Alternatives. This

problem is adequately discussed in the DCS Architectural Issues subsection. Here we simply point out that it is analytically related to the assumptions made in the problems of (1) and (2) above.

(4) Subproblem d, Network Analysis. Given the predictions of (1) and (2) above, and a specific DCS alternative from (3) above, find the performance characteristic of that alternative.

(5) Subproblem e, Management. It is likely that in the multitude of DCS alternatives, many will be so close to each other in performance characteristics that clear cut quantitative choices cannot be made. In fact, a particular DCS alternative may not be uniformly dominant under variations in W or D. In this case the range of competing DCS alternatives must be submitted to further analysis with respect to other DCS "ilities." Many of these ilities can only be evaluated subjectively; hence, management must exercise its prerogative in choosing between the remaining alternatives and a desired (U_b, U_a(W)).

(6) Subproblem f, Refinement. The solutions to the preceding five problems narrow down the range of far-term DCS choices by specifying a partitioning, a switching technology, a hierarchical structure, and a mix of media. An approximate sizing is also found. At this point more detailed work can begin on the development of transition plans and hardware related issues of reliability, maintainability, and availability. Issues of flexibility, interoperability, and restorability, as well as security may also be studied in some depth since the issues have been appropriately scoped into the context of a fairly specific future DCS architecture. This report stops short of considering these issues beyond this point.

III. APPROACH

"... let us first of all understand the problem as a whole."[6]

1. SCOPING THE PROBLEM

The preceding chapter has defined the DCS technical planning problem in terms of four technically oriented subproblems given in section II, 3,c. Problem e depends on management to select one (or more) DCS alternative(s) out of a set which may be indistinguishable under the four preceding technical problems. Having focused the DCS alternatives to a small number by these efforts now allows detailed engineering work to commence with the selected alternative as a basis, as indicated in problem f.

The sequence of subproblems in DCS technical planning was arrived at through consideration of "high level" architectural issues. We suspect that, realistically, these issues cannot be addressed independently, and so one of our problems is to develop a methodology which can consider their interaction. In order to accomplish this the problem must be stated in concrete terms, i.e.,:

a. What is the objective of planning? Ours is to maximize the DCS performance characteristic (Figure 8).

b. What are the variables? Ours are:

(1) DCS alternatives, defined in section II, 3,b; this includes partitioning alternatives and switching technology alternatives

defined in section II, 3,a.

(2) Hardware assumptions, given in the sets of section II, 2. The range of hierarchical structures and mix of media issues are embedded in these.

c. What are the constraints? Ours are

(1) A total DCS Budget, D, given in section II, 2.

(2) Demands for service, given in the requirements matrices of section II, 1.

(3) The adversary's attack resources, W, given in section II, 3. It does not seem reasonable to attempt a single computer program to solve this problem. The reasons are straightforward enough. There are an extremely large number of possible DCS alternatives, and the generation of the performance characteristic (or an approximation) for a single alternative requires the solution of a sequence of network design problems of large size.

A preferable approach would use an interaction between man and machine. In this approach a man would select from files on the machine a specific DCS alternative and a set of hardware assumptions for analysis. The machine would then compute the corresponding performance characteristic for inspection by the man. By iterating this procedure a heuristic model involving both man and machine is created. Such an approach allows the design of a computer program to solve the simpler problem below.

Given:

a. A specific DCS alternative

b. A specific set of hardware assumptions

c. The requirements matrices

d. The DCS budget constraint

e. The adversary's attack resources.

Find:

The associated performance characteristic.

This problem is very similar to the work ordinarily performed within R700. The differences are in degree. To solve the DCS architectural development problem, it is necessary to increase the range of assumptions that can be made in alternatives and hardware, and automate the overall evaluation process. This can be done through the performance characteristic measurement and the interactive procedure mentioned above.

2. METHODOLOGY

The present network design tools being used for DCS System Design planning efforts have been developed over a number of years and have played an important role in the continuing upgrading and optimizing of DCS plans [8,9,10]. However, in considering the total spectrum of future architectural concepts that are under consideration, it may well be necessary to develop specific tradeoffs for which modelling tools have not yet been developed. The remainder of this section discusses the requirements and characteristics needed for such architectural design tools.

a. The Range of DCS Designs. The problem under consideration is the discovery of the major design features (say a more detailed architectural plan) of the future DCS. This DCS may comprise one or

several large scale communication network(s); this is a parameter to be discovered. If more than one network is indicated, the user community served, possible gateways, the type(s) of service provided, and the amount of traffic handled by each network must be discovered. For each network in the future DCS, the most efficient division of functions between the access area and backbone designs must be uncovered; e.g., the hierarchical definition. This involves selecting the number, loading, and functions of local switches, concentrators, backbone switches and their interconnections in a cost effective way. Naturally this means that CER's must be developed for each class of hardware, with the independent variables being the implementation scheme, loading, function, and, where applicable, number of terminations.

The principal technical issues in the network design problem can be seen as the following:

(1) Statistical multiplexing of two generic types of traffic needs to be considered in a network design context. The two generic traffic types are described by:

(a) "Long" holding times; i.e., traffic which is best matched by circuit switched networks.

(b) "Short" holding times; i.e., traffic which is best matched by packet switched networks.

Note that some specific traffic types, e.g., facsimile, may be mapped into either of the generic types above and the economic impact on DCS design of such options merits consideration.

(2) Access area/backbone design interaction needs to be

studied in the absence of externally (and possibly arbitrarily) imposed constraints. This issue may have significant impact on both the economics and the survivability of the DCS, and certainly is a key issue in using network design tools to deduce future hardware developments needed in the DCS.

(3) Satellite/terrestrial networks design interaction needs to be studied and can only be reasonably approached by a design tool which simultaneously considers both. A more realistic attitude would be to consider a single network comprising both terrestrial and satellite components.

(4) The network design tools necessary to scope the far term DCS must be capable of coping with roughly 1,000 traffic sources (user installations) and perhaps 2,000 to 3,000 nodes (major hardware devices, exclusive of terminal equipment and local switches).

The complexity of this problem is indicated in Figures 10, 11 and 12. The figures are developed from the user installation outward into the DCS. Suppose, for example, that there were 1,000 user installations to be serviced. Then there are the same number of local switches interconnected through an as-yet unknown number of concentrators and backbone switches. Also unknown are the numbers of satellites and satellite terminals and the richness of the interconnection matrix for all hardware. The problem is further compounded by not knowing the optimum functional characterization of the hardware or the best partitioning (see Figures 5 and 6). In any problem of this magnitude, it is necessary

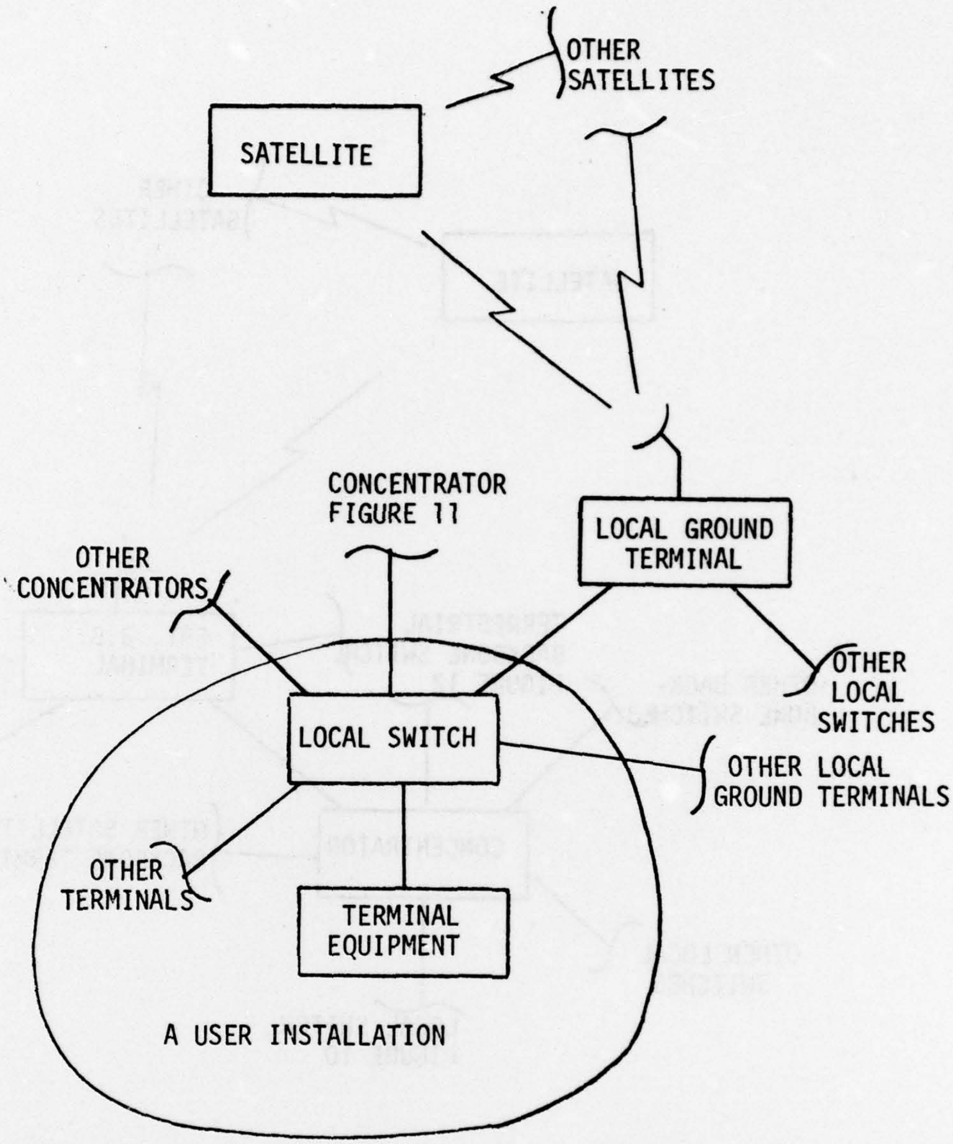


Figure 10. Interconnection possibilities for a local switch

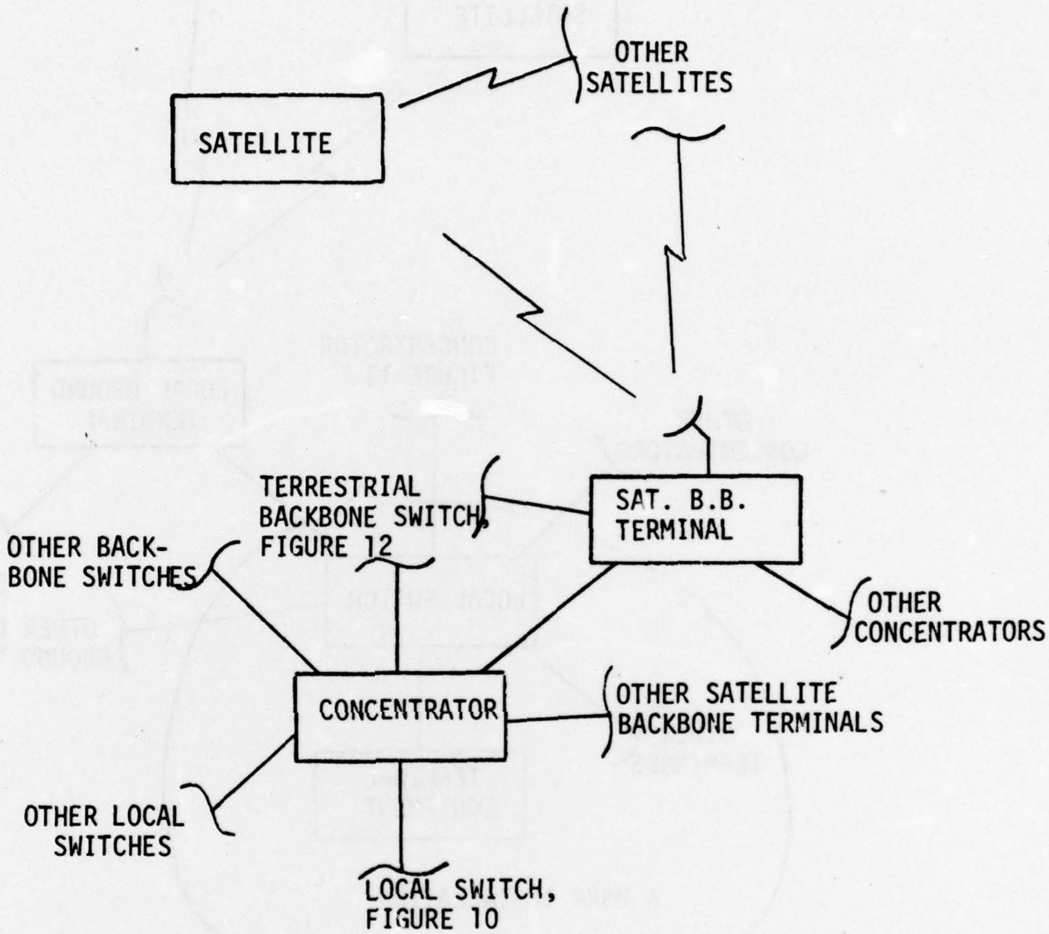


Figure 11. Interconnection possibilities for a concentrator

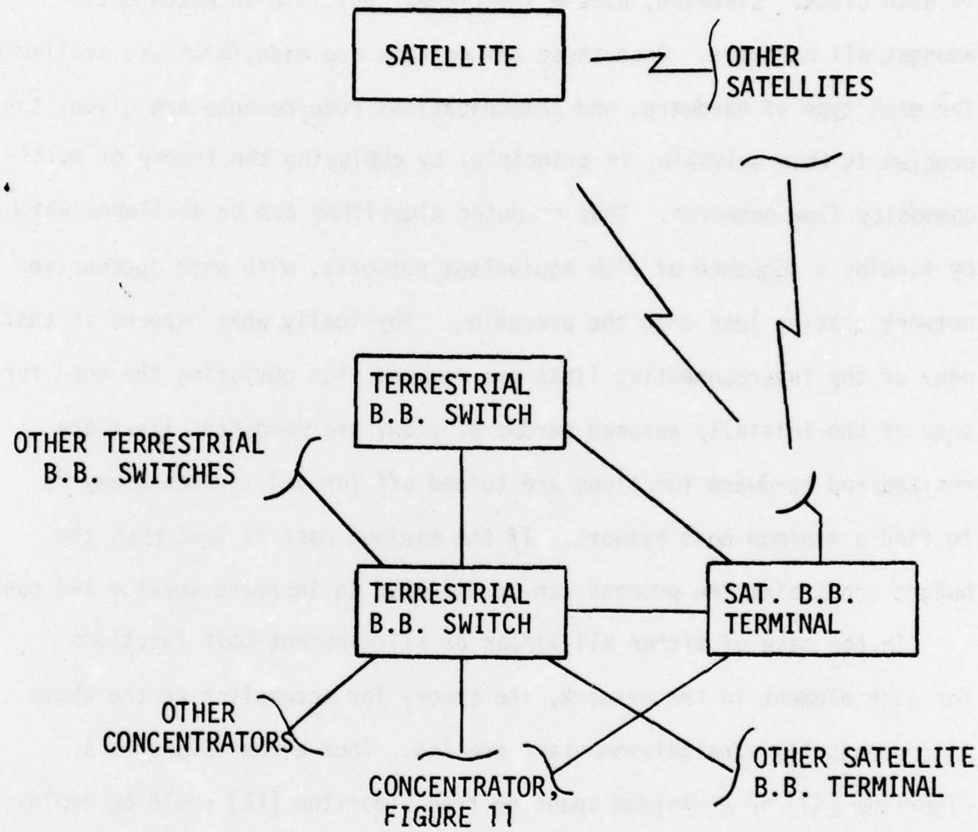


Figure 12. Interconnection possibilities for a terrestrial backbone switch

that the major features be abstracted and heuristic approaches developed to find a solution.

b. A Heuristic Approach. An obvious first approach to the numerical problem above is initially to assume overly large populations of hardware in each class. Likewise, assume the richest possible interconnection amongst all hardware. Once these assumptions are made, CER's are available for each type of hardware, and communications requirements are given; the problem is then solvable, in principle, by employing the theory of multi-commodity flow networks. Thus computer algorithms can be developed which operate by finding a sequence of flow equivalent networks, with each successive network costing less than the preceding. Physically, what happens is that many of the interconnecting links are removed, thus obviating the need for some of the initially assumed hardware; flows are rerouted; links are resized; and hardware functions are turned off (or on) in such a way as to find a minimum cost network. If the minimum cost is less than the budget constraint, the process can be iterated to increase service and cost.

In the case of either all-linear or all-constant cost functions for each element in the network, the theory for accomplishing the above is conceptually straightforward and precise. Thus either Dijkstra's algorithm [11] or a minimum spanning tree algorithm [12] could be employed in principle. In practice neither of the cost-function situations holds. This, compounded by the magnitude of the problem, forces consideration of using the above computer algorithms, in conjunction with heuristic approaches and gradient techniques, to find locally optimum solutions in a reasonably short time.

A flow chart depicting the interrelationships of the various technical problems and a first cut approach for handling the overall issue is shown in Figure 13. The first four boxes at the top of the figure represent data collection exercises discussed in section II. Each of these may be done independently, but must conform to the mathematical requirements of the computer model which manipulates the data. The data gathered represent a morphological base covering the foreseeable range of future DCS alternatives. It is in an unorganized form however; i.e., it does not constitute a communications system, only the components. An analogy would be a menu from which to choose and arrange a dinner.

The next box, "SELECT A SPECIFIC DCS ALTERNATIVE," is a human activity. Here the human selects a consistent subset out of the morphological base and the machine is then required to evaluate the selection. Thus, it is important that the data in the morphological base be formatted in a manner consistent with both machine requirements and the human's need for subjectively organized labelling. The formats of section II should fill both needs.

The box, "SET UP AN INITIAL RICHLY CONNECTED NETWORK," is the first step in the machine activity for evaluating the given DCS alternative. If machine memory and computation time permit, the initial network should be completely connected. Otherwise algorithms to aggregate or "cluster" the user installations, thereby reducing the number of hardware devices, will be required. Efficient clustering will depend on the DCS alternative to be evaluated.

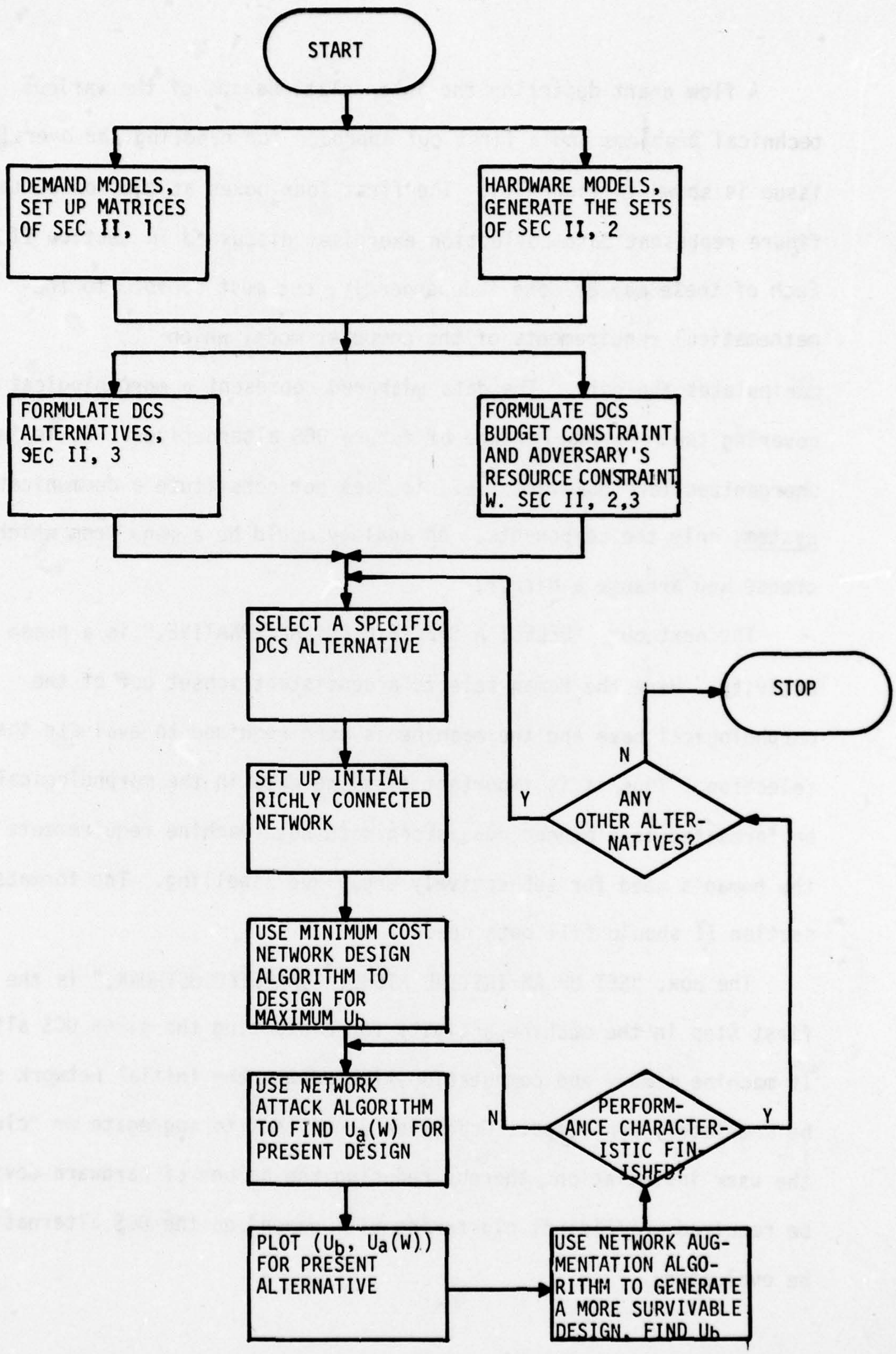


Figure 13. Flow Chart for DCS Architectural Development/Evaluation

The box, "USE MINIMUM COST NETWORK DESIGN...," can be developed from the network design techniques presently used at DCEC. Major extensions required are the ability to design integrated (voice/data) networks, increasing the scope to handle access area/backbone tradeoffs, satellite/terrestrial tradeoffs, and multiple networks with associated gateway and budget allocation problems.

The remaining boxes are used to develop the performance characteristic, and associated sequence of network designs, for a given DCS alternative. The basic idea is to derive successively more survivable designs from the first design which maximized U_b. To accomplish this the machine games the "design-attack-redesign-attack-..." situation in the lower loop. The point of view adopted in this loop is that the value of attacked resources in the present design is freed up for reallocation in the next design.

IV. EPILOGUE

The statement of the DCS architectural development/evaluation problem given in section II.3, c and the flow chart for the process of Figure 13 should be used as guidelines in the DCS architectural efforts. The problem statement is admittedly incomplete, but it provides a necessary starting point for improvement. Any improvements in the problem statement must be couched in concrete terms since an equivocal problem statement can only result in equivocal solutions.

The overall architectural development/evaluation problem consists of a number of subproblems needing further development, namely:

1. SUBPROBLEM A, PREDICTION OF DEMANDS

Crisis communications requirements should be determined in the formats of section II, 1. The requirements should not be referenced in any way to the physical DCS since such predictions can be regarded as "self fulfilling prophecies." Requirements predictions should be made in the context of foreseeable needs for information exchange among using installations under crisis conditions. The DCS should then be planned to meet these needs. Solving this problem is an essential part of the total and will require the continuing effort of a number of experts. It is recommended that a study to generate these data be initiated.

2. SUBPROBLEM B, PREDICTION OF TECHNOLOGY AND COST

The range of possible hardware devices with which the DCS could

be constructed is very large. A convenient means of aggregating the possibilities is given in the formats of section II, 2. These formats, along with the mechanism of Figure 13, will allow DCS planners to deduce the functional nature of preferable hardware for the DCS and initiate development action when the indicated hardware is not already available. By modifying the CER's to reflect lease/buy options, the consequences in terms of the total system can be determined. This problem too is an essential and difficult piece of the total and should be staffed accordingly. A study in this area should be initiated.

3. SUBPROBLEM C, FORMULATION OF ALTERNATIVES

DCS alternatives cannot be assessed unless they are couched in concrete terms. The data formats suggested for subproblems a and b provide a mechanism for describing both the range and specific choices for DCS alternatives in an unequivocal way. As mentioned above, the problem herein is incomplete. Efforts to improve the problem statement by adding new dimensions amount to adding to the range of alternatives. The obvious difficulty is in adding new dimensions to the problem statement in such a way that they are concrete; the new subproblems posed are amenable to technical solution, and the total problem remains tractable. It is difficult to pin down how this can be done. What can be done is to insist that outputs from the formulators be well-defined and that the overall technical planning mechanism remains self consistent.

4. SUBPROBLEM D, NETWORK ANALYSIS

Network analysis is a major element of the architectural development/ evaluation mechanism. A realistic assessment of a given DCS alternative

can be made only by using this tool. The existing models will require considerable modification and extension to create the mechanism of Figure 13. Continuing research will be necessary to improve these tools, since network problems of such large size dictates that heuristics have to be employed. In addition, the design tools are expandable in that new dimensions will be added as the problem statement is improved. These considerations point to the need for the implementation and improvement of design tools/processes such as indicated in Figure 13.

A process which is not understood cannot be controlled. The first step in improving the DCS design process is documentation. The publication of study results is insufficient. Documentation concerned with how the overall process works is essential for visibility (goal-oriented behavior) and to elicit concrete, constructive criticisms for improving the process. Similar documentation is necessary for individual efforts contributing to the overall process. The intent is to produce documentation of the operational procedures and assumptions used in the technical efforts supporting management. Specifically, such items as: problem definition, approach, data formats (when interface with other problem areas is required), and relation of the part to the whole, should be published for each of the subproblems. The documentation should be updated on a continuing basis as the planning mechanism and factors evolve.

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